

The top threshold effect in the $\gamma\gamma$ production at the LHC

Pankaj Jain,^{1,*} Subhadip Mitra,^{2,†} Prasenjit Sanyal,^{1,‡} and Ravindra K. Verma^{1,3,§}

¹Department of Physics, Indian Institute of Technology Kanpur, Kanpur 208 016, India

²Center for Computational Natural Sciences and Bioinformatics,

International Institute of Information Technology, Hyderabad 500 032, India

³Department of High Energy Physics, Tata Institute of Fundamental Research, 1 Homi Bhabha Road, Mumbai 400 005, India

We compute the top quark threshold contributions to the $\gamma\gamma$ production at the LHC. These contributions become significant when the invariant mass of the photon pair, $M_{\gamma\gamma}$ just exceeds two times the mass of the top quark and induce some features in the $M_{\gamma\gamma}$ distribution, a hint of which is already visible in the recent data. We determine the magnitude of this threshold effect and investigate kinematic cuts which may enhance its significance.

I. INTRODUCTION

The $\gamma\gamma$ pair production in proton-proton colliders such as the LHC plays a very important role in the search for new physics. Recently this channel has attracted considerable attention due to a potential hint of new physics [1–3]. Hence it is important to determine the background, *i.e.*, the Standard Model (SM) contribution to this channel as reliably as possible. The background generally shows a smooth behaviour with respect to the invariant mass of the photon pair ($M_{\gamma\gamma}$), as indicated, for example, by the background-only fit obtained by the ATLAS collaboration [1]. However, at the threshold of production of a new particle, this smooth feature can get disturbed. In this letter, we shall primarily look at the top quark threshold effect that appears about $M_{\gamma\gamma} \sim 350$ GeV, a kinematic region not far off from the region where the hint of new physics was observed.

The $\gamma\gamma$ pair production at the LHC gets contribution from several parton level sub-processes, including the quark anti-quark annihilation ($q\bar{q} \rightarrow \gamma\gamma$) at the leading order (LO), the quark-gluon scattering ($qg \rightarrow q\gamma\gamma$) at the next-to-leading order (NLO) in QCD and the gluon fusion process ($gg \rightarrow \gamma\gamma$) at the next-to-next-to-leading order (NNLO) in QCD [4–6]. The top threshold effect appears in the gluon fusion process that occurs through the fermion loop diagrams, like the one shown in Fig. 1 (the box diagram). It arises from the destructive interference between the top loop diagrams containing on-shell top quarks and other diagrams containing light quark loops. Once $M_{\gamma\gamma}$ exceeds two times the mass of the top quark, $m_t \approx 173$ GeV, the gluon fusion process gets contribution from on-shell tops in the box loop, creating a dip in the invariant mass distribution [4, 7, 8].

The precise nature of the threshold effect can be seen explicitly in Fig. 4 of [7]. It shows the ratio of the cross sections of the gluon fusion process computed with $m_t = 173$ GeV to that obtained by setting $m_t = \infty$ at the 14 TeV LHC. In other words, it shows the correction due to the top loop to the gluon fusion process. This ratio is found to be equal to unity for $M_{\gamma\gamma} < 200$ GeV. As $M_{\gamma\gamma}$ increases, the ratio starts to de-

crease and shows a sudden dip at about $M_{\gamma\gamma} = 2m_t$. After the dip, it rises smoothly and eventually saturates to a value of approximately 1.75 for $M_{\gamma\gamma} \approx 1600$ GeV. Note, however, there is nothing special about the top quark or about this process, similar dips are also predicted at the threshold of each new particle in the light by light scattering [9].

Though this threshold effect exists, *a priori* it is not clear whether it can be observed since the gluon fusion gives a sub-dominant contribution to the two photon production [4, 10–15]. As mentioned, the leading order contributions arise from the quark anti-quark annihilation process. Fortunately, the NLO as well as NNLO contributions are relatively large for the $\gamma\gamma$ pair production [15]. The gluon fusion process, although higher order in strong coupling in comparison to the quark anti-quark annihilation process, is not negligible and gives a significant contribution [5, 6, 15]. This may be further enhanced by imposing some kinematical cuts. An even higher order contribution to this, classified as NNNLO, has also been computed [6]. It is found to be small but not negligible.

It is intriguing that the ATLAS data [1] already show a hint of a dip at $M_{\gamma\gamma} \approx 2m_t$, exactly where it is expected. However, more data is required to conclude whether this is a statistical fluctuation or not. In this letter, we compute the $pp \rightarrow \gamma\gamma$ production process at NLO QCD and the $gg \rightarrow \gamma\gamma$ process to determine whether the top quark threshold effect can be observed at the 13 TeV LHC. Motivated by the hint in the data, here we mostly follow the ATLAS analysis for kinematic cuts. But we also explore additional cuts that may enhance the threshold contribution.

Observation of this phenomenon is interesting by itself but it may also be useful to understand the relative magnitudes of different contributions. Theoretically, these have significant uncertainties due to the unknown higher order contributions. Furthermore, if the effect can be observed with sufficient accuracy, it may also provide another measurement of the top quark mass.

II. COMPUTATIONS AND RESULTS

We compute both the $gg \rightarrow \gamma\gamma$ process and the NLO $pp \rightarrow \gamma\gamma(j)$ process at the 13 TeV LHC in the MADGRAPH5-AMC@NLO [16] environment with NN23LO1 parton density functions (PDFs) [17] and PYTHIA6 [18] for

* pkjain@iitk.ac.in

† subhadip.mitra@iiit.ac.in

‡ psanyal@iitk.ac.in

§ ravindkv@iitk.ac.in, ravindra.verma@tifr.res.in

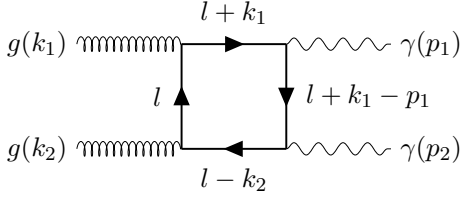


FIG. 1. The top quark loop diagram contributing to $gg \rightarrow \gamma\gamma$.

parton showers (PS). Throughout our analysis, we only consider photons with transverse energy, $E_T^\gamma > 25$ GeV. For $M_{\gamma\gamma} \geq 200$ GeV, the cross section for the gluon fusion is about 270 fb. It reduces to about 115 fb once we impose the following additional cuts from the ATLAS analysis [1] on the two E_T ordered photons,

$$E_T^{\gamma_1} > 0.4M_{\gamma\gamma}, \quad E_T^{\gamma_2} > 0.3M_{\gamma\gamma}. \quad (1)$$

We show the invariant mass distribution obtained from the $gg \rightarrow \gamma\gamma$ process in Fig. 2. For this plot, we have first generated 100,000 events with $M_{\gamma\gamma} \geq 200$ GeV in the gluon fusion channel alone and then applied the cuts defined in Eq. (1) on these events to clearly demonstrate the threshold effect. The red line in the top panel is a smooth fit of the simulated events. The fitting function is taken to be of the same form as used by ATLAS [1],

$$f_0(x; b, a_0) = (1 - x^{1/3})^b x^{a_0}, \quad x = M_{\gamma\gamma}/\sqrt{s}. \quad (2)$$

We determine the parameters a_0, b from the range 200 GeV $< M_{\gamma\gamma} < 1000$ GeV. The top threshold effect can be seen in the bottom panel of Fig. 2 where we have shown the difference between the simulated events and the smooth fit. The errorbars shown represent the square-root of the number of events in each bin (\sqrt{N}). We see a clear dip in the cross section approximately at the position of twice the top quark mass.¹

However, as described before, the total $pp \rightarrow \gamma\gamma$ cross section is dominated by other lower order sub-processes. This can be seen in Fig. 3 where we combine the events from the $gg \rightarrow \gamma\gamma$ process with the events from the NLO $pp \rightarrow \gamma\gamma(j)$ process (matched with PS) for about 40 fb⁻¹ of integrated luminosity. Once the cuts defined in Eq. (1) are applied, the cross section of the NLO $pp \rightarrow \gamma\gamma(j)$ process for $M_{\gamma\gamma} \geq 200$ GeV becomes about 570 fb compared to 115 fb in the gluon fusion channel. As expected, the dip now becomes less significant than the gluon fusion only case, though it is still visible. In order to get a rough estimate, we notice that, at its minimum position, the dip is roughly a 10% effect if we consider only the gluon fusion process. Since this contributes only 20% of the total cross section, the effect is 2% of the total. Hence a one sigma observation requires about 2500 events in the bin centred at $M_{\gamma\gamma} \approx 2m_t$,

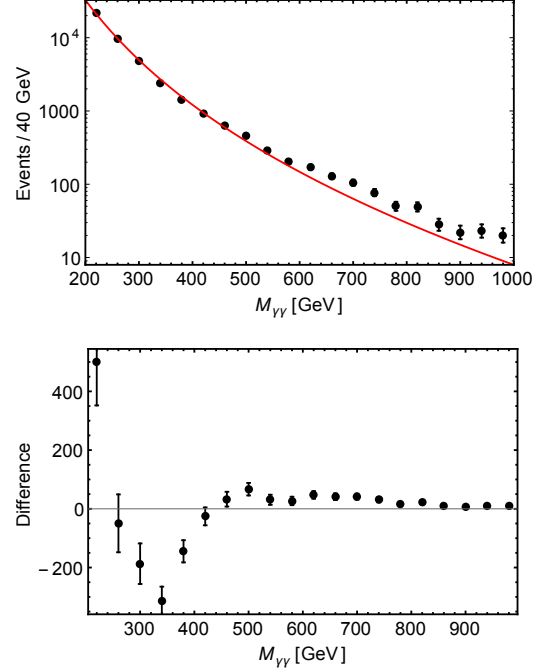


FIG. 2. (Top plot) The invariant mass distribution of the two photons from the gluon fusion process. These events are obtained after applying the cuts defined in Eq. (1). The solid line shows a smooth fit of the binned events. (Bottom plot) The difference between the simulated events and the smooth fit. A clear dip is seen at $M_{\gamma\gamma} \approx 2m_t$.

which is consistent with the result seen in Fig. 3. We point out that the dip is rather broad and spreads over several bins. Hence the significance of the cumulative effect is higher than the one sigma value quoted above. As we shall argue below, the threshold effect will be seen at the LHC once sufficient data becomes available.

A. A new cut on the $\gamma\gamma$ system

We next explore the possibility of enhancing the significance of the dip by imposing different kinematical cuts that are less restrictive on the gluon fusion channel. In particular, when we relax the $M_{\gamma\gamma}$ dependent cuts of Eq. (1), the number of events in the bin corresponding to $M_{\gamma\gamma} = 340$ GeV increase by a factor of roughly four (see Fig. 4). Hence we expect a 2 sigma detection of the dip in this bin, again in rough agreement with the simulation result shown in Fig. 4 (top plot). However, without the $M_{\gamma\gamma}$ dependent E_T cuts, though the gluon fusion cross section increases to about 270 fb for $M_{\gamma\gamma} \geq 200$ GeV, the corresponding cross section of the NLO $pp \rightarrow \gamma\gamma(j)$ process becomes much larger, about 2.8 pb (i.e., the gluon fusion contribution becomes even less than 10% of the NLO $pp \rightarrow \gamma\gamma(j)$ process).

We next define a variable C related to the centrality of the

¹ Note that the fit is not very precise at the low values of $M_{\gamma\gamma}$ (~ 200 GeV), but this happens because of the limitations of the simple form of the fitting function in Eq. (2).

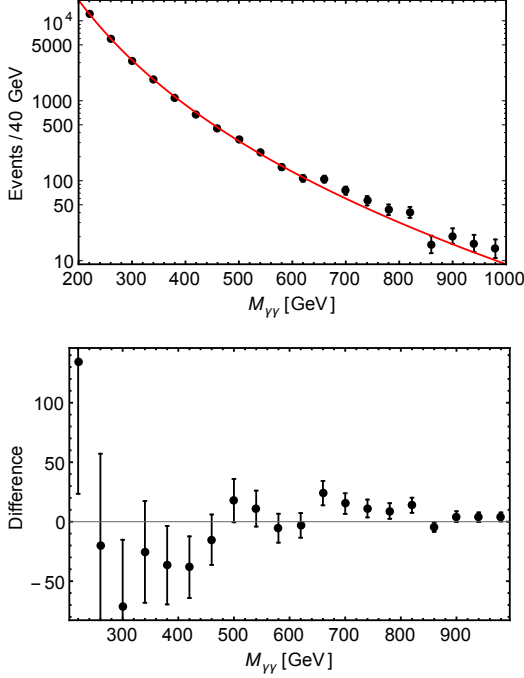


FIG. 3. (Top plot) The invariant mass distribution of the two photons from the combined gluon fusion and the NLO $pp \rightarrow \gamma\gamma(j)$ processes obtained after applying cuts defined in Eq. (1). The solid line shows a smooth fit of the binned events. (Bottom plot) The difference between the simulated events and the smooth fit.

$\gamma\gamma$ system as,

$$C = \frac{|\vec{P}_{\gamma_1} + \vec{P}_{\gamma_2}|}{M_{\gamma\gamma}} \quad (3)$$

where \vec{P}_{γ_1} and \vec{P}_{γ_2} denote the 3-momenta of the outgoing photons in the lab frame. Clearly, when the lab frame coincides with the center of mass frame of the two outgoing photons $C = 0$. Now, if we demand C to be smaller than or equal to some fixed number C_0 (say), depending on the choice of C_0 such a cut could affect the $q\bar{q}$ or gq initiated processes more than the gg initiated one. (This is possible because the valence quark PDFs peak at very different value of x in comparison to those of the sea quarks and gluons.) In Fig. 5, we show the ratio of the cross-sections of two subprocesses, the gluon fusion and the NLO QCD $pp \rightarrow \gamma\gamma$ for different values of C_0 .

From Fig. 5 we see that the contribution of $gg \rightarrow \gamma\gamma$ is about 20 % of the contribution of the NLO $pp \rightarrow \gamma\gamma(j)$ process for C_0 between 0.5 to 1. However, with decreasing C_0 , the total number of events also decreases substantially and so, we need to optimize the value of C_0 . For Fig. 4 (bottom plot), we choose $C_0 = 2$, which is a reasonable compromise. In this figure, the upper plot is obtained without any cut on C [i.e., $C_0 \rightarrow \infty$ and also without the ATLAS $M_{\gamma\gamma}$ dependent cuts defined in Eq. (1)] whereas the lower plot is obtained with $C_0 = 2$. From this it is clear that the cut on C enhances the significance of the threshold effect. Note,

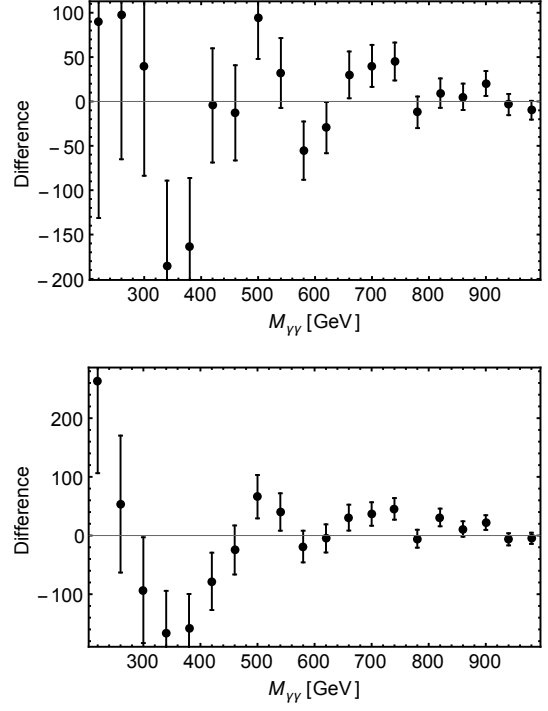


FIG. 4. (Top plot) The difference between the binned events and their smooth fit (see text) obtained from the combined gluon fusion and the NLO $pp \rightarrow \gamma\gamma(j)$ processes with an integrated luminosity of about 40 fb^{-1} . These events are obtained without the cuts defined in Eq. (1). (Bottom plot) The same difference but now with the cut, $C \leq 2$ [see Eq. (3)].

here we have focused only on the bin at $M_{\gamma\gamma} = 340 \text{ GeV}$. But, as mentioned before, the dip spreads over several bins. Hence, if we include these nearby bins too in our estimations, the combined significance of the dip is much higher than a two sigma effect at this luminosity. Hence the effect will be seen in the near future since the chosen luminosity is within the reach of the LHC.

Finally, before we conclude, we note that there could be another source of top threshold effect in the photon pair production channel. Just as the gluon splitting creates $c\bar{c}$ and $b\bar{b}$ pairs that contribute in the sea quark density of a proton, once the top threshold is crossed, one could also imagine $t\bar{t}$ pairs appearing in the sea (i.e. a ' t -PDF'). Hence, additional threshold effects would arise due to the processes $t\bar{t} \rightarrow \gamma\gamma$ and $tg \rightarrow t\gamma\gamma$. If, naively, one assumes that the ' t -PDF' at a scale Q is roughly given by the b -PDF at the scale Qm_b/m_t , the contributions of these processes turn out to be much smaller than the effect considered here. It is not easy to quantify this argument, as the behaviour of this density function near the top threshold won't be captured properly. However, since the top quark is much heavier than the b -quark, it is reasonable to assume that these processes are unlikely to produce any observable features with the present luminosity, though they might be important for precision studies.

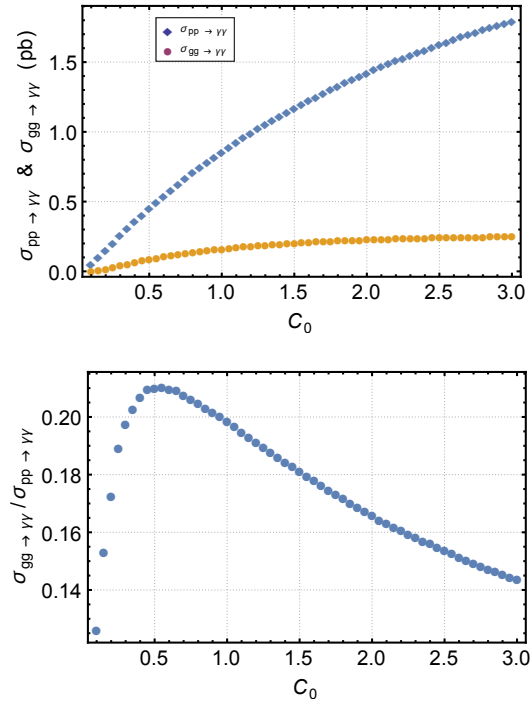


FIG. 5. The effects of the cut $C \leq C_0$ [see Eq. (3)] on the gluon fusion and the NLO $pp \rightarrow \gamma\gamma(j)$ processes obtained without the cuts defined in Eq.(1). The cross sections are obtained for $M_{\gamma\gamma} \geq 200$ GeV.

III. SUMMARY AND CONCLUSIONS

In this letter we have investigated the top quark threshold effect in the two photon channel at the LHC. This effect arises in the loop mediated $gg \rightarrow \gamma\gamma$ subprocess due to the

destructive interference between top loop diagrams containing on-shell top quarks and other light quark loop diagrams. It appears as a dip in the invariant mass distribution of the photon pair near two times the mass of the top quark.

Though a hint of this effect can already be seen from the present ATLAS data, observing this dip with a large statistical significance would require more data. Within the SM, the gluon fusion process is overshadowed by the NLO (QCD) $pp \rightarrow \gamma\gamma(j)$ process that has a larger cross-section. However, here, we have argued that this can be mitigated to some extent by judicious choices of kinematical cuts. We have demonstrated this by defining a new cut on the gamma gamma system. Though it is beyond the scope of this letter, it might be possible to make the threshold effect even more prominent with sophisticated techniques like multivariate analysis etc.

It will be very interesting to observe this SM effect more accurately at the LHC. However, there are other motivations to look into this in detail. It can provide us another way to probe the top-mass experimentally. Not only this, threshold effects can also tell us about some beyond the SM fermions indirectly. Since this effect arises from the interference effects, any heavy fermion that can run in the loop of the $gg \rightarrow \gamma\gamma$ process would lead to such a threshold effect. Hence, observation (or non-observation) of any such effect in the gamma gamma spectrum could let us infer about new heavy coloured fermions carrying non-zero electromagnetic charge in a model independent manner.

IV. ACKNOWLEDGMENTS

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